

## **LOW MODAL BIREFRINGENT WAVEGUIDES AND METHOD OF FABRICATION**

### **Field of the Invention**

**[0001]** The present invention relates to optical waveguides in general, and, more particularly, to surface waveguides.

### **Background of the Invention**

**[0002]** A surface waveguide is a light-guiding element, much like an optical fiber, which is formed on the surface of a rigid substrate. Although constrained to the substrate, the surface waveguide can traverse any path in the plane of the surface including curves, loops, and relatively sharp corners, subject to design constraints based on the optical properties of the materials used to form the surface waveguide. Surface waveguides are widely used in many applications including telecommunications, chemical sensing, and force sensing.

**[0003]** A surface waveguide is characterized as having a central region or "core" and a surrounding "cladding." An optical signal travels through a surface waveguide as an optical mode propagating through the core. The optical signal is confined to the core by the cladding. The guiding property of a surface waveguide stems from a difference in the speed at which light travels in the material of the core versus the material of the cladding. Light travels at different speeds in different materials, and every material has a "refractive index,"  $n$ , which is a measure of the speed of light in that material versus the speed of light in vacuum.

**[0004]** When light traveling in one material hits a boundary of a new material with a different refractive index, the light will reflect off the boundary, be bent (*i.e.*, refract, as in a prism), pass through into the new material, or some combination thereof. The amount of light that is reflected, as compared to the amount of light that passes into the new material depends on the relative refractive indices of the materials and the angle at which the light hits the boundary. In the case of a surface waveguide, the refractive index of the cladding is typically only slightly lower than the refractive index of the core. Furthermore, light traveling in the core travels in a direction that is nearly parallel to the interface between the core and the cladding. Therefore, when light traveling in the core hits the boundary with

the cladding, nearly all of the light bounces back into the core in the same way that a flat stone bounces off the surface of a pond when it's skipped. The propagating mode is, therefore, effectively confined to the core.

**[0005]** Surface waveguides can be fabricated in various forms including slab waveguides, ridge waveguides, and stripe waveguides. A slab waveguide comprises a planar thin film of optical core material sandwiched between two planar thin films of cladding material. The cladding material above and below the core slab confine the propagating optical mode in the vertical direction, but not in the horizontal direction.

**[0006]** A ridge waveguide is similar to a slab waveguide, but in addition to a slab region also includes a protruding ridge of material through which an optical mode propagates. The lateral and vertical structure substantially confines the mode in both dimensions, except where the ridge meets the slab. It is possible that a mode can exist in the slab area outside the ridge portion.

**[0007]** A stripe waveguide is a ridge waveguide wherein the slab layer has been etched completely away except in the ridge area. Since there is no core material anywhere except in the stripe, an optical mode will propagate only in the core.

**[0008]** The material used for the core and cladding are chosen based on their relative optical properties. Surface waveguides have been formed from a variety of materials, including different types of glasses (*e.g.*, silicon dioxide, boro-phosphosilicate glass, phosphosilicate glass, *etc.*), silicon nitrides, silicon oxy-nitrides, gallium arsenide, indium phosphide, silicon, and lithium niobate. These materials are used in combination to enhance the guiding ability of the surface waveguide. The most common surface-waveguide material is glass, wherein core and cladding glasses are doped with different impurities or different concentrations of the same impurity in order to make the refractive index of the cladding glass slightly lower than the refractive index of the core glass to provide light-guiding capability.

**[0009]** The surface waveguide is formed by successively depositing and patterning thin films of optical materials onto the surface of a substrate. Low pressure chemical vapor deposition (LPCVD) is a common method of forming the thin-film layers. In an LPCVD system, the glass is deposited onto the surface of a silicon wafer in high temperature furnaces into which different precursor gasses are injected, resulting in a chemical reaction that deposits glass on the silicon wafer surface.

**[0010]** The deposition conditions and the types of gasses can be changed to produce various glass types having different optical and mechanical properties. In addition, deposition conditions and precursor-gas type affect the way the resulting film covers features on the surface. Certain gas mixtures or materials are known to result in what are called "conformal" layers, wherein the thickness of the deposited film is nearly uniform over underlying structure. Materials that deposit conformally during LPCVD include polycrystalline silicon, silicon dioxide deposited using a precursor gas of tetraethylorthosilicate, (this type of silicon dioxide will hereinafter be referred to as "**TEOS**"), and stoichiometric silicon nitride (silicon nitride that has the exact formulation of three silicon to every four nitrogen atoms:  $\text{Si}_3\text{N}_4$ ).

**[0011]** Unfortunately, conformally- and nonconformally-deposited thin films exhibit inherent residual stress due to the deposition process itself and due to the material characteristics of the films, such as differences in thermal expansion coefficients. If the underlying films or substrate include surface topography, then such stresses can be directionally dependent as well.

**[0012]** The refractive index of a pure, unstrained, non-crystalline material is always exactly the same at a specific temperature. For example, pure, unstrained silicon dioxide ( $\text{SiO}_2$ ) has a refractive index of exactly 1.46 at room temperature (300 K). By adding an impurity (e.g., phosphorous, etc.) and controlling its concentration, however, the refractive index of silicon dioxide can be altered. Different concentrations or impurities are used to vary the refractive index as desired within materially-defined limits. The refractive index of most materials can be controlled in the same way, and the ability to control the refractive index in this manner is exploited in surface-waveguide and optical-fiber technology alike.

**[0013]** There are other factors that will cause the refractive index of a material to change. Some of these factors include a variation in temperature, internal stress caused by the presence of impurities, and mechanical strain. Often, these factors are directional, such as a thermal gradient through the thickness of a layer, differences in the vertical and horizontal dimensions of a waveguide, or a mechanical force applied in only one plane. As a consequence, the refractive index of such a material becomes directionally dependent. That is, there are two refractive indices for the material. Such a material is said to be *birefringent*.

**[0014]** A surface waveguide supports the propagation of light that has two directionally-dependent components, referred to as polarization modes  $T_E$  and  $T_M$ . These polarization modes are essentially flat sinusoidal waves that are orthogonal (*i.e.*, physically oriented at right angles to each other), with the  $T_E$  mode being horizontally oriented and the  $T_M$  mode being vertically oriented. Due to directionally-dependent stress resulting from thin-film deposition, the polarization modes in a typical surface waveguide see significantly different refractive indices. This is known as “**modal birefringence**”, and is quantified as  $n_{TE} - n_{TM}$ . Modal birefringence is particularly prevalent in ridge and stripe waveguides, wherein the core material is patterned to have a roughly square cross-section and subsequently over-coated with a conformal layer of cladding material, exacerbating stress and stress gradients present in the different layers.

**[0015]** Modal birefringence has thus far limited the utility of surface waveguide structures. For most applications using optical fibers or surface waveguides, it is necessary that the two polarization modes travel through the surface waveguide at the same speed. Divergence of the modes as they travel can lead to serious system complications for many applications. In a communications system, for example, it is well understood that dire consequences result from differences in the received optical power of the polarization modes, or the time at which the polarization modes are received, or when optical power transfers from one polarization mode to the other. It is highly desirable therefore, to form surface waveguides having low modal birefringence.

### **Summary of the Invention**

**[0016]** The illustrative embodiment of the present invention is a waveguide having low modal birefringence and a method for fabricating the waveguide. A waveguide in accordance with the illustrative embodiment has a composite guiding region that is sandwiched by a lower cladding layer and an upper cladding layer. The lower and upper cladding layers serve to confine propagating light to the composite guiding region in well-known fashion.

**[0017]** In accordance with the illustrative embodiment, the composite guiding region is structured so that it exhibits a “balanced stress configuration.” This means that the stress in the direction that aligns with the  $T_E$  polarization mode is substantially equal to the stress in the direction that aligns with the  $T_M$  polarization mode. Since the stress configuration is

balanced, the refractive indices seen by the  $T_E$  and  $T_M$  modes will be substantially equal. The result is a waveguide that exhibits very low modal birefringence.

**[0018]** In some embodiments, the composite guiding region comprises multiple optically-transparent layers that have different stress characteristics. The stress characteristics of the layers are selected to yield a balanced stress configuration. As a consequence, the amount of modal birefringence exhibited in the composite guiding region is independent of the transmission properties of the layers that compose it.

**[0019]** In the illustrative embodiment, the composite guiding region comprises three layers. The residual stresses of these layers are used to tailor the stress in the composite guiding region. In some embodiments, the materials chosen for these layers are selected so that stress characteristic of layers bottom and top layers is opposite in sign to the stress characteristic of the middle layer. In other words, if the middle layer exhibits compressive stress, then the bottom and top layers exhibit tensile stress and visa versa.

**[0020]** In some embodiments, the illustrative embodiment of the present invention comprises:

- a composite guiding region having at least three layers, wherein:

- two of said three layers have stress of the same sign;

- said two layers are separated by one or more interposed layers;

- said one or more interposed layers have stress of opposite sign relative to said two layers; and

- said interposed layers are suitable for guiding light based on the relative refractive indices of said interposed layers and said two layers.

### **Brief Description of the Drawings**

**[0021]** Figure 1 depicts a cross-sectional view of a waveguide having a composite guiding region in accordance with the illustrative embodiment of the present invention.

**[0022]** Figure 2 depicts a perspective view of a waveguide in accordance with the illustrative embodiment, wherein the composite guiding region comprises a plurality of layers.

**[0023]** Figure 3 depicts a method in accordance with the illustrative embodiment of the present invention.

[0024] Figure 4A depicts a first variation of the waveguide depicted in FIG. 2.

[0025] Figures 4B-4G depicts the waveguide of Figure 4A at various stages of fabrication.

[0026] Figure 5 depicts a second variation of the waveguide depicted in FIG. 2.

[0027] Figure 6 depicts a third variation of the waveguide depicted in FIG. 2.

[0028] Figure 7 depicts a fourth variation of the waveguide depicted in FIG. 2.

[0029] Figure 8A depicts a fifth variation of the waveguide depicted in FIG. 2.

[0030] Figure 8B-8G depicts the waveguide of Figure 8A at various stages of fabrication.

### **Detailed Description**

[0031] Figure 1 depicts a cross-sectional view of a portion of a stripe waveguide in accordance with the illustrative embodiment of the present invention. Stripe waveguide **100** comprises composite guiding region **106**, which is surrounded by lower cladding layer **102** and upper cladding layer **104**. The material(s) that compose lower cladding layer **102** and upper cladding layer **104** have a refractive index that is lower than the materials that compose composite guiding region **106**. By virtue of this difference in refractive indices, the lower and upper cladding layers serve to confine propagating light to composite guiding region **106**.

[0032] In accordance with the illustrative embodiment of the present invention, composite guiding region **106** is structured so that it exhibits a "balanced stress configuration." As used herein, the phrase "**balanced stress configuration**" means that the stress in the direction that aligns with the  $T_E$  polarization mode is substantially equal to the stress in the direction that aligns with the  $T_M$  polarization mode. If the stress configuration in a waveguide is balanced, then the refractive indices seen by the  $T_E$  and  $T_M$  modes will be substantially equal, or in other words, the waveguide will have low modal birefringence.

[0033] In some embodiments, composite guiding region **106** comprises multiple optically-transparent layers that have different stress characteristics. The stress characteristics of the layers are selected to yield a balanced stress configuration. As a consequence, the amount of modal birefringence exhibited in the composite guiding region

is independent of the transmission properties of the layers that compose it. An example of a multi-layered composite guiding region is depicted in Figure 2, which is a perspective view of stripe waveguide **200** having axis of signal propagation **214**.

**[0034]** As depicted in Figure 2, composite guiding region **106** comprises layers **208**, **210**, and **212**. Layers **208** and **212** sandwich interposed layer **210**. Composite guiding region **106** is itself sandwiched by lower cladding layer **102** and upper cladding layer **104**.

**[0035]** Composite guiding region **106** can also be described as including an inner core (*i.e.*, layer **210**) and an outer core, wherein the outer core includes a lower portion (*i.e.*, layer **208**) and an upper portion (*i.e.*, layer **212**). While both descriptions are correct, one or the other might be preferable as being more descriptive of a particular variation of composite guiding region **106**. These two alternate descriptions will be used interchangeably within this specification.

**[0036]** In stripe waveguide **200**, the residual stresses of layers **208**, **210** and **212** are used to tailor the stress in composite guiding region **106**. In some embodiments, the materials chosen for layers **208**, **210**, and **212** are selected so that stress characteristic of layers **208** and **212** is opposite in sign to the stress characteristic of layer **210**. In other words, if layer **210** exhibits, for example, compressive stress, then layers **208** and **212** exhibit tensile stress. Alternatively, if layer **210** exhibits tensile stress, then layers **208** and **212** exhibit compressive stress.

**[0037]** Figure 3 depicts method **350**, suitable for forming a waveguide having a composite guiding region, such as composite guiding region **106** depicted in Figure 2. Method **350** recites, in operation **352**, forming a lower cladding layer (*e.g.*, lower cladding layer **102**, *etc.*). The lower cladding layer (in conjunction with the upper cladding layer) confines a propagating optical signal within the composite guiding region. In some embodiments, the lower cladding layer comprises silicon dioxide. A more extensive list of suitable materials is provided later in this specification.

**[0038]** In operation **354**, the outer core lower portion (*e.g.*, layer **208** in Figure 2) is deposited or grown on the lower cladding layer. In other words, in operation **354**, the bottom layer of composite guiding region **106** is formed. In some embodiments, such as a stripe waveguide, operation **354** includes the task of patterning the outer core lower portion. Compare Figure 2, for example, wherein layer **208** is a patterned layer, with Figure 5, an embodiment of a ridge waveguide, wherein layer **508** is not patterned.

**[0039]** In operation **356**, a material that forms the inner core is deposited or grown on the outer core lower portion. The inner core corresponds to interposed layer **210** in FIG. 2. When forming a stripe or ridge waveguide, as depicted in the Figures that accompany this specification, operation **356** includes the task of patterning the inner core.

**[0040]** Implicit in operations **354** and **356** is that, in selecting materials for the layers, the inner core (interposed layer) exhibits a residual stress of opposite sign relative to that of the outer core lower portion.

**[0041]** In operation **358**, the outer core is completed with the deposition or growth of the outer core upper portion (e.g., layer **212** in Figure 2), wherein a layer of material is deposited or grown on the inner core. The outer core upper portion advantageously conforms to the underlying topography of the outer core lower portion and the patterned inner core. In some embodiments, operation **358** includes the task of patterning the outer core upper portion. As previously described, the lateral extent of the outer core upper portion affects the stress distribution (*i.e.*, uniformity and directionality of stress) in the composite guiding region. Implicit in operation **358** is that, in selecting a material for the outer core upper portion, it exhibits a residual stress of the same sign as the outer core lower portion. In some embodiments, the upper and lower portions of the outer core are formed of the same material, while in some other embodiments, different materials are used for the two layers.

**[0042]** Method **350** also includes optional operation **360** wherein an electro-optic functionality is added. In some embodiments, operation **360** comprises depositing or growing, and then patterning, a layer of electro-optically active material on the composite guiding region (see, e.g., Figure 6, layer **614**). Suitable electro-optic materials include without limitation, zinc-oxide (ZnO), lead-zirconium titanate (PZT), lanthanum-doped PZT (PLZT), barium titanate, lithium niobate, and electro-optic polymers. In some embodiments, the electro-optically active material is zinc-oxide, which can be used to induce electro-optic effects such as piezo-electric, photo-elastic, acousto-optical effects.

**[0043]** In operation **362**, an upper cladding layer (e.g., layer **104** in Figure 2) is deposited or grown on the outer core upper portion (and/or the layer of electro-optically active material, if present).

**[0044]** Regarding materials selection, stoichiometric materials are well-suited for use in forming composite guiding region **106** because they exhibit a characteristic residual



stress that is consistent regardless of the manner in which the materials are deposited. For example, stoichiometric silicon nitride exhibits residual *tensile* stress of approximately 1 GPa, thermally-grown silicon dioxide exhibits residual *compressive* stress of approximately 500 MPa, and TEOS exhibits residual *compressive* stress of approximately 300 MPa. In some embodiments, layer **210** comprises TEOS and layers **208** and **212** comprises stoichiometric silicon nitride. In some other embodiments, layer **210** comprises thermally-grown silicon dioxide and layers **208** and **212** comprise stoichiometric silicon nitride. In yet some additional embodiments, layer **210** comprises stoichiometric silicon nitride while layers **208** and **212** comprise silicon dioxide.

**[0045]** With the materials chosen in this manner, the thickness and lateral dimensions of each of layers **208**, **210**, and **212** are used to control the stress profile through the bulk of composite guiding region **106**. In particular, the thickness of the layers are used to adjust the magnitude of the stress and the lateral dimensions of the layers affect the direction of the stress (*i.e.*, along the axes that align with the  $T_E$  polarization mode and the  $T_M$  polarization mode) to obtain a balanced stress configuration in accordance with the present disclosure.

**[0046]** The calculation of the stress configuration in composite guiding region **106** is quite complex and usually performed using simulation software, such as OlympIOs, available from C2V of Enschede, The Netherlands. Layer thickness and lateral dimensions can be determined via simulation using a trial-and-error process. In particular, for a given structural configuration and materials, multiple simulations are performed wherein layer thickness is varied. The layer thickness that results in the smallest value for the difference between the  $T_E$  polarization mode and the  $T_M$  polarization mode provides the lowest modal birefringence. Those skilled in the art will know an approximate dimension for the various layer thicknesses, and these can be used as a starting point for the simulations.

**[0047]** It is understood by those skilled in the art that the residual stress and stress gradients of a thin-film layer is a function of many parameters, including, without limitation, the differences in the coefficients of thermal expansion between the deposited layer and underlying layers or substrate, the doping level of the layer, material structure, and deposition conditions. Those skilled in the art will know how to manipulate these parameters, in conjunction with the thickness and lateral dimensions, to achieve a balanced stress configuration.

**[0048]** A more extensive list of materials that are suitable for use as the upper and lower cladding layers as well as the layers of the composite guiding region includes, but is not limited to, stoichiometric silicon nitride, silicon dioxide, silicon, polysilicon, silicon carbide, silicon monoxide, silicon-rich silicon nitride, indium phosphide, gallium arsenide, indium-gallium arsenide, indium-gallium arsenide-phosphide, lithium niobate, silicon oxy-nitride, phosphosilicate glass, and borophosphosilicate glass. In addition, compounds such as silicon nitride are effectively different materials with different material properties when their composition is other than stoichiometric, and these different material compounds can be used in combination in similar fashion to those listed above. In view of the present disclosure, those skilled in the art will know to appropriately select materials, such as those listed above, as a function of their stress characteristic, to enable a balanced stress configuration in composite guiding region **106**.

**[0049]** Figure 4A depicts stripe waveguide **400**, which is a variation of stripe waveguide **200**. Figures 4B-4G depict stages in the fabrication of stripe waveguide **400**.

**[0050]** Referring to Figure 4A, stripe waveguide **400** comprises composite guiding region **106**, which includes outer core lower portion **408**, inner core **410**, and outer core upper portion **412**. Composite guiding region **106** is disposed on lower cladding **102** and covered by upper cladding **104**.

**[0051]** Figure 4B depicts layer **102** of material (e.g., silicon dioxide, etc.) in nascent stripe waveguide **400**. Layer **102** is deposited or grown on a substrate (not depicted). Layer **102** will serve as the lower cladding for stripe waveguide **400**, See operation **352** of method **300**.

**[0052]** Figure 4C depicts layer **407** of material, which is grown or deposited on layer **102**. Layer **407** will form the outer core lower portion. See, operation **354** of method **300**. In some embodiments, layer **407** is stoichiometric silicon nitride ( $\text{Si}_3\text{N}_4$ ), which will deposit conformally on layer **102** in an LPCVD deposition furnace.

**[0053]** Figure 4D depicts layer **409** of material, which is grown or deposited on layer **407**. Layer **409** will form the inner core or interposed layer of composite guiding region **106**. See, operation **356** of method **300**. In some embodiments in which layer **407** is stoichiometric silicon nitride, layer **409** is TEOS. In such embodiments, layer **409** will deposit conformally on layer **407**.

[0054] Figure 4E depicts layers **407** and **409** after patterning, which defines the shape of outer core lower portion **408** and inner core **410** of composite guiding region **106**. See operations **354** and **356** of method **300**.

[0055] Figure 4F depicts layer **411** of material, which is grown or deposited on the top and along the sides of inner core **410** and outer core lower portion **408**. See, operation **358** of method **300**. In some embodiments in which layer **407** is stoichiometric silicon nitride, layer **411** comprises a second conformal layer of stoichiometric silicon nitride. After deposition of layer **411**, inner core **410** is completely surrounded by outer core material, thereby completing composite guiding region **106**.

[0056] Figure 4G depicts layer **411** after patterning, wherein the shape of outer core upper portion **412** is defined. See, operation **358** of method **300**. The purpose of patterning outer core upper portion **412**, which is an optional operation, is to tailor the effect that this portion of the outer core has on the stress distribution in composite guiding region **106**. A goal of this tailoring being, of course, to reduce modal birefringence in stripe waveguide **400**.

[0057] Stripe waveguide **400** takes final form as upper cladding **104** is grown or deposited on outer core upper portion **412**. See, Figure 4A and operation **362** of method **300**. In some embodiments, upper cladding **104** is a combination of a second conformal layer of TEOS, and a layer of a different glass having a lower stress, such as borophosphosilicate glass (BPSG). In conjunction with lower cladding **102**, upper cladding **104** confines propagating light to composite guiding region **106**.

[0058] It will be clear to those skilled in the art, after reading this specification, how to make and use other embodiments of the present invention wherein the various layers of waveguide **400** are selected from other materials in the list of suitable materials provided above, as well as any other materials that are found to be suitable.

[0059] It will be also be clear to those skilled in the art, after reading this specification, how to make and use other embodiments of the present invention wherein outer core upper portion **412** extends a different distance along lower cladding **104**, and how to make and use embodiments that utilize air, rather than a layer of material, as upper cladding **104**.

[0060] Figure 5 depicts a cross-sectional view, orthogonal to the axis of signal propagation, of ridge waveguide **500**, which is another variation of waveguide **200**. In waveguide **500**, composite guiding region **106** comprises a portion of layer **508**, layer **510**, and layer **512**. Layer **508** forms the outer core lower portion and layer **512** is the outer core upper portion. The portion of layer **508** that is located directly below interposed layer **510** is a part of composite guiding region **106**, while the remainder of layer **508** serves to tailor the stress configuration of the composite guiding region. Layer **102** serves as a lower cladding, and layer **104** serves as the upper cladding for waveguide **500**. Although layer **508** is shown as extending to the edge of lower cladding **102**, it will be clear to those skilled in the art, after reading this specification, how to make and use other embodiments of the present invention wherein layer **508** is patterned to extend any suitable distance from the edge of interposed layer **510**.

[0061] Figure 6 depicts a cross-sectional view, orthogonal to the axis of signal propagation, of stripe waveguide **600**, which is another variation of the waveguide **200**. In waveguide **600**, composite guiding region **106** comprises layer **608**, interposed layer **610**, and layer **612**. Layer **612** is a conformal layer that covers the top and sides of interposed layer **610**. The thickness of layer **612** is the substantially the same at both the top and sides of interposed layer **610**. Layers **608** and **612** comprise an outer core and interposed layer **610** comprises an inner core. Consequently, the inner core and outer core collectively compose composite guiding region **106** of waveguide **600**. Layer **102** serves as a lower cladding, and layer **104** serves as the upper cladding for waveguide **600**. The addition of layer **612** to both the top and sides of interposed layer **610** enables greater control over the stress configuration in composite guiding region **106** since layer **612** affects the stress in interposed layer **610** in both lateral and vertical directions. Low modal birefringence in waveguide **600** is achieved via proper design of the geometry of composite guiding region **106** and by controlling the thickness of layers **608** and **612**.

[0062] In waveguide **600**, layer **612** is present only in composite guiding region **106**. But in some other embodiments, layer **612** extends beyond the composite guiding region, and is disposed on at least a portion of layer **102**. Its presence on layer **102** affects the stress configuration in composite guiding layer **106**. The presence of layer **612** on layer **102**, and the extent of its coverage, therefore provides an additional measure of control over stress in composite guiding layer **106**. It will be clear to those skilled in the art, after

reading this specification, how to make and use other embodiments of the present invention wherein layer **612** extends further along layer **102** (see, e.g., Figure 4A).

[0063] Waveguide **600** also includes layer **614**, which comprises an electro-optically active material. In some embodiments, layer **614** is zinc oxide. The electro-optically active material can be activated through an external electric field, applied perpendicular to the substrate, to induce a change in the effective index of waveguide **600**. One benefit of the presence of electro-optically active material is an ability to dynamically correct for errors in fabrication or environmental variations such as temperature changes.

[0064] Furthermore, in accordance with the present invention, in some embodiments, electro-optically active material is incorporated into waveguide **600**, or any of the other waveguides discussed herein, to create an attenuator, splitter, equalizer or like optoelectronic devices. To create a splitter, for example, a change in refractive index is induced to direct an optical signal along either one of two paths. In an attenuator or an equalizer (a multi-channel attenuator), refractive index is changed to alter guiding properties, and, ultimately, the received signal strength of the optical signal.

[0065] Figure 7 depicts a cross-sectional view, orthogonal to the axis of signal propagation, of stripe waveguide **700**, which is yet another variation of waveguide **200**. In stripe waveguide **700**, lower cladding **104** is replaced by lower cladding **716**, which includes planar field region **718** and raised region **720**. Layer **104** forms an upper cladding for waveguide **700**.

[0066] As depicted in Figure 7, composite guiding region **106**, which comprises layers **708**, **710**, and **712**, is disposed on raised region **720**. Layer **712** is a conformal layer that covers the top and sides of interposed layer **710** with a substantially equal thickness. Layer **712** also coats the sidewalls of raised region **720**, creating a stress in raised region **720** that affects the stress configuration in composite guiding region **106**. The height of raised region **720** and the material and thickness of layer **712** are chosen such that the modal birefringence of composite guiding region **106** is reduced to a low level.

[0067] In Figure 7, layer **712** is shown covering some amount of planar field region **718**; however, it will be clear to those skilled in the art, after reading this specification, how to make and use other embodiments of the present invention wherein layer **712** exists only on the top and sidewalls of raised region **720** and layers **708** and **710**, or alternatively extends for a suitable distance beyond the edge of composite guiding region **106**.

[0068] Table 1 below provides dimensions of the various layers of waveguides **500**, **600**, and **700**, for an embodiment in which:

- the lower cladding layer is thermally-grown silicon dioxide;
- the outer core lower portion (of the composite guiding region) is silicon nitride;
- the inner core (of the composite guiding region) is TEOS;
- the outer core upper portion (of the composite guiding region) is silicon nitride;
- the widths of the composite guiding regions listed for waveguides **600** and **700** include the thickness of the outer core deposited on the sidewalls of the inner core; and
- the upper cladding layer comprises TEOS and an additional lower stress glass such as BPSG.

More particularly, Table 1 provides ranges for the thickness of the various layers, wherein thicknesses within the ranges will provide a waveguide having a relatively low modal birefringence. Furthermore, the preferred thickness will yield a relatively low modal birefringence in comparison within other thicknesses within the indicated range.

		Raised Feature Dimensions (nm)		Lower Cladding Thickness (nm)	Upper Cladding Thickness (nm)	Outer Core Lower Portion Thickness (nm)	Outer Core Upper Portion Thickness (nm)	Inner Core Thickness (nm)	Comp. Guiding Region Width (nm)
		Width	height						
Ridge Waveguide 500	Range			100 – 30,000	100 – 1350	10 – 350	10 – 350	100 – 1000	10 – 2000
	Preferred	N/A	N/A	5,000	5,000	250	250	200	1000
Stripe Waveguide 600	Range			100 – 30,000	100 – 1350	10-350	10 – 350	100 – 1000	100-1000
	Preferred	N/A	N/A	5,000	5,000	250	250	700	700
Stripe Waveguide 700	Range	10-2000	0 – 2000	100 – 30,000	100 – 1350	10 – 350	10 – 350	100 – 1000	100-1000
	Preferred	800	800	5,000	5,000	250	250	300	300

**Table 1:** Design parameters for surface waveguide embodiments

**[0069]** It will be clear to those skilled in the art, after reading this specification how to make and use other embodiments of the present invention comprising layers chosen from any of the following list of materials, including, but not limited to, stoichiometric and non-stoichiometric compounds of silicon nitride, silicon dioxide, TEOS, silicon, polysilicon, silicon carbide, silicon monoxide, silicon-rich silicon nitride, indium phosphide, gallium arsenide, indium-gallium arsenide, indium-gallium-arsenide-phosphide, lithium niobate, silicon oxynitride, phosphosilicate glass, and BPSG.

**[0070]** Figure 8A depicts inverted-ridge waveguide **800**, which is a variation of waveguide **200**. Figures 8B-8G depict stages in the fabrication of inverted-ridge waveguide **800**. In inverted-ridge waveguide **800**, lower cladding **104** is replaced by lower cladding **822**, which includes planar field region **824** and recessed region **826**. Layer **104** forms an upper cladding for waveguide **800**.

**[0071]** Referring to Figure 8A, inverted-ridge waveguide **800** comprises composite guiding region **106**, which includes outer core lower portion **808**, inner core **810**, and outer core upper portion **812**. Composite guiding region **106** is disposed in recessed region **826** of lower cladding **822**, and is covered by upper cladding **104**.

**[0072]** Figure 8B depicts layer **822** of material (e.g. silicon dioxide, etc.) in nascent inverted-ridge waveguide **800**. Layer **822** is deposited or grown on a substrate (not depicted). Recessed region **826** is formed in layer **822** by removing material (e.g. through etching, ion milling, etc.) from a region of planar surface **824**.

**[0073]** Figure 8C depicts layer **807** of material, which is grown or deposited on layer **822** in a manner that results in layer **807** being a conformal layer. Layer **807** will form the outer core lower portion. See, operation **354** of method **300**. In some embodiments, layer **807** is stoichiometric silicon nitride ( $\text{Si}_3\text{N}_4$ ), which will deposit conformally on layer **822** in an LPCVD deposition furnace.

**[0074]** Figure 8D depicts layer **809** of material, which is grown or deposited on layer **807** in a manner that results in layer **809** being a conformal layer. Layer **809** will form the inner core or interposed layer of composite guiding region **106**. See, operation **356** of method **300**. In some embodiments, layer **809** is TEOS which will deposit conformally on layer **807** in an LPCVD deposition furnace.

[0075] Figure 8E depicts layers **807** and **809** after patterning, which defines the shape of outer core lower portion **808** and inner core **810** of composite guiding region **106**. See operations **354** and **356** of method **300**.

[0076] Figure 8F depicts layer **811** of material, which is grown or deposited on planar surface **824** of layer **822**, outer core lower portion **808**, and inner core **810**. See, operation **358** of method **300**. In some embodiments in which layer **807** is stoichiometric silicon nitride, layer **811** comprises a second conformal layer of stoichiometric silicon nitride. After deposition of layer **811**, inner core **810** is completely surrounded by outer core material, thereby completing composite guiding region **106**.

[0077] Figure 8G depicts layer **811** after patterning, wherein the shape of outer cladding upper portion **812** is defined. See, operation **358** of method **300**. After patterning, layer **812** extends beyond the edge of composite guiding region **106** and is disposed on at least a portion of layer **822**. Its presence on layer **822** affects the stress configuration in composite guiding region **106**. The presence of layer **812** on layer **822**, and the extent of its coverage, therefore provides an additional measure of control over stress in composite guiding layer **106**. It will be clear to those skilled in the art, after reading this specification, how to make and use other embodiments of the present invention where layer **811** extends further along layer **822** (see, e.g., Figure 4A) or is completely removed from planar field region **824** of layer **822**, thereby forming a stripe waveguide embodiment of waveguide **200**.

[0078] Inverted-ridge waveguide **800** takes final form as upper cladding **104** is grown or deposited on outer core upper portion **812**. See, Figure 8A and operation **362** of method **300**. In some embodiments, upper cladding **104** is a combination of a second conformal layer of TEOS and a layer of a different glass having a lower stress, such as BPSG. In conjunction with lower cladding **822**, upper cladding **104** confines propagating light to composite guiding region **106**.

[0079] It will be clear to those skilled in the art, after reading this specification, how to make and use other embodiments of the present invention wherein the various layers of waveguide **800** are selected from the list of suitable materials provided above, as well as any other materials that are found to be suitable.



**[0080]** It will also be clear to those skilled in the art, after reading this specification, how to make and use other embodiments of the present invention that utilize air, rather than a layer of material, as upper cladding **104**.

**[0081]** Table 2 below provides dimensions of the various layers of waveguide **800**, for an embodiment in which:

- the lower cladding layer is thermally-grown silicon dioxide;
- the outer core lower portion (of the composite guiding region) is silicon nitride;
- the inner core (of the composite guiding region) is TEOS;
- the outer core upper portion (of the composite guiding region) is silicon nitride;
- the width of the composite guiding region listed includes the thickness of the outer core deposited on the sidewalls of the inner core; and
- the upper cladding layer comprises TEOS and an additional lower stress glass such as BPSG.

More particularly, Table 2 provides ranges for the thickness of the various layers, wherein thicknesses within the ranges will provide a waveguide having a relatively low modal birefringence. Furthermore, the preferred thickness will provide yield a relatively low modal birefringence in comparison within other thicknesses within the indicated range.

		Recessed Feature Dimensions (nm)		Lower Cladding Thickness (nm)	Upper Cladding Thickness (nm)	Outer Core Lower Portion Thickness (nm)	Outer Core Upper Portion Thickness (nm)	Inner Core Thickness (nm)	Comp. Guiding Region Width (nm)
		Width	height						
Inverted-Ridge Waveguide <b>800</b>	Range	200 – 2000	200- 2000	100 – 30,000	100 – 1350	10 – 350	10 – 350	20 – 1850	40 – 4400
	Preferred	800	550	5,000	5,000	250	250	300	800

Table 2: Design parameters for one embodiment of inverted-ridge waveguide **800**,

**[0082]** It is to be understood that the above-described embodiments are merely illustrative of the present invention and that many variations of the above-described embodiments can be devised by those skilled in the art without departing from the scope of the invention. For example, in this specification, numerous specific details are provided in

order provide a thorough description and understanding of the illustrative embodiments of the present invention. Those skilled in the art will recognize, however, that the invention can be practiced without one or more of those details, or with other methods, materials, components, *etc.*

**[0083]** Furthermore, in some instances, well-known structures, materials, or operations are not shown or described in detail to avoid obscuring aspects of the illustrative embodiments. It is understood that the various embodiments shown in the Figures are illustrative, and are not necessarily drawn to scale. Furthermore, the particular features, structures, materials, or characteristics can be combined in any suitable manner in one or more embodiments. It is therefore intended that such variations be included within the scope of the following claims and their equivalents.